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THE EFFECT OF LOW FREQUENCY RADIO WAVES ON BIOLOGICAL MATERIALS

Progress Report
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OBJECTIVES: To investigate the effects of low frequency radio waves on viable seeds of *Zea maize*, as a function of frequency, intensity and exposure length.

SUMMARY OF RESULTS:

A. Since start of project.

Work on irradiation of seeds has been nearly completed with the exception of further exploration in the 20 megacycle region. The studies at 5000 cycles have been completed with both Golden Bantam and Ear-Bred varieties of seeds. The statistical breakdown of the results on Golden Bantam was given in the last report. Work on the Ear-Bred seeds is so similar in results that the test series cannot be distinguished from each other. Tesla coil irradiation was carried out at frequencies of 125 Kc, 147 Kc, 175 Kc and 200 Kc. No differences between seed varieties was observed here. At none of the above frequencies can any statistically significant lethal effect be demonstrated.

It was hoped that work at higher temperatures might lead to further information. The frequency series noted above have been reproduced at 47°C and at 55°C, but here again there is no reliable sign of a lethal effect due to the fields. The fields used have been applied for periods up to eight hours, and with intensities of up to 10,000 volts per centimeter.

A point of some interest with regard to prolonged exposure to high fields is the negligible rise in temperature observed in the seeds. With a knowledge of the frequency, dissipation factor, and dielectric

constant, it is easily shown that temperature rises of the order of 5°C per hour may be expected. However, in no case has more than 3°C for a total period of eight hours been observed. This is due to the limited validity of the commonly used method of calculation, which assumes isothermal conditions, which apparently are not existent within the seeds.

The only important changes of temperature have been observed during irradiation at 60 cps with an effective field of 60 kilovolts peak. Under these conditions a rise of 22°C was measured after a 2 hour exposure, contrasted with the calculated rise of 74°C.

The initial work on the measurements of dielectric constants and dissipation factor has been extended to the frequency range of 10 megacycles. This is shown for Golden Bantam at room temperature in Figure 1. No significant discontinuities may be seen in these curves, although above 900Kc the effects of lead inductance have made the readings rather variable. At the low frequency end of the curves the rise of dielectric constant and large increase in dissipation factor is common to both varieties of seeds, although there is a strong temperature dependence which largely removes these increases at low temperatures.

B. Current period.

Clear cut lethal effects are produced when the seeds are exposed to 20 megacycles at 800 volts rms for periods of 4 1/2 hours. The heating effect under these conditions is pronounced.

Measurements of dissipation factor versus frequency as a function of temperature have been extended to 10 megacycles, and the two varieties

of corn compared with sunflower seeds. Figure 3 shows representative curves. Measurements were also made to compare dehydrated seeds with those frozen. Figure 2 shows clearly that freezing and dehydration have similar effects on the dissipation factor.

The quantities measured during the past and present report periods have been used to construct graphs showing the variation of equivalent parallel resistance with frequency. There is a close similarity between these curves for various conditions, as shown in Figure 4. Two electrical models have been examined, either of which may give curves similar to those in Figure 4.

Continued search for a substance non-injurious to corn, with a very high dielectric strength, and low dielectric constant, has been unsuccessful so far.

PLANS FOR FUTURE:

Immediate: A rearrangement of the temperature control system surrounding the dielectric measurement cell is most desirable to reduce the effects of lead inductance at high frequencies. When this is accomplished it is hoped to repeat most of the curves which have questionable points to obtain better consistency in the data.

If equipment becomes available, the work will be extended to still higher frequencies. It is hoped that we may obtain continuous curves of dissipation and dielectric constant at several temperatures up to 1000 megacycles.

With the improved data, curve fitting experiments will be undertaken to select a good model to explain the curves of parallel resistance

vs. frequency. Measurements must also be made to determine whether the dependence of DC resistance on field strength is non-ohmic.

Long Range: The frequency spectrum will be examined for evidence of molecular absorption. We shall also try to gather information on the charge, mobility, and perhaps species of ions responsible for the low frequency effects observed.

DETAILED PROGRESS

Investigation of extremely high field effects has been hampered by the lack of a good dielectric. It is necessary to immerse the seeds in a dielectric, expose them to the field, and then remove the dielectric and germinate the seeds. However, the materials tried have had uniformly bad effects on the germination. The combination of low dielectric constant, high dielectric strength, and no chemical effect on the seed is available with some transformer potting materials, for instance, but these pose the serious difficulty of removal so that germination tests may be conducted. Most of the organic solvents have damaging effects. Various transformer oils have shown the most promise, but these seem to penetrate the seeds and kill them. It is hoped that we may secure some samples of High-boiling Freons or similar substances to continue this work.

A variable frequency oscillator which will produce 200 watts CW became available and has been used to irradiate the seeds at higher frequencies. A series of preliminary tests at 20 megacycles shows 42% germination for seeds exposed 4 1/2 hours at 800 volts rms. This is in contrast to the standard germination of 96% for these seeds.

Unfortunately no record of the actual temperature attained was taken, although the seeds are quite hot to the touch after the exposure. No sign of scorch or burn was noticed. These results have not yet been thoroughly investigated due to the arrival of a General Radio Type 821 Bridge.

This bridge has made it possible to extend the range of our measurements up to at least 10 megacycles, although nominally they could go to 40 megacycles. However, it was found that the points obtained at ranges above 10 megacycles have poor reproducibility, due entirely to the variation in lead inductance between experiments. As presently constituted, it is necessary to run a self-supporting parallel line from the bridge terminals to the dielectric test condenser. The test condenser must be several inches from the bridge, due to the arrangement of the heating and cooling devices. The unavoidable movement of the cell and temperature controls between filling and emptying the cell has produced changes in the inductance, which though small, have an appreciable effect on the measurements at higher frequencies. General Radio does furnish an elaborate system for corrections, which have been applied in some trials, but these are still not too reliable, at least above 15 megacycles or so.

Graphs 1 and 3 indicate the form taken by the dissipation factor as a function of changing frequency and temperature. We are not too interested in the variation of the dielectric constant at the present time, although of course the data for its computation is available from the dissipation factor measurements.

It has been observed in all cases that heating and cooling the seeds has a strong effect on the dissipation factor and a moderate effect on the dielectric constant. The magnitude of the change in dissipation depends not only on the temperature but on the frequency at which the measurement is taken. Figure three indicates how the low frequency-high temperature curve rises above that taken at roughly room temperature, while at higher frequencies, the room temperature curve becomes higher. There is no apparent mathematical relationship here between change in dissipation and change in temperature.

During this period we also obtained a Boonton 160-A "Q-meter" for checking the results of the two General Radio bridges. This instrument has a useful range of from 50 Kc to 75 megacycles, although as previously mentioned, lead inductances prevent good readings at the highest frequencies. One of the most useful benefits of this instrument is its ability to bridge the transition zone between the upper range of our low frequency bridge and the low frequency range of our high frequency bridge. Both bridges are slightly unreliable at the extreme ends of their ranges, despite the corrections offered by General Radio Company. We now have data which is perfectly reliable in this transition zone, and some of it is used in plotting Figure 4.

At the same time it was thought useful to try some completely different type of seed, both as to chemical constitution and shape. Sunflower seeds were selected as being a useful type, since they differ in size and shape and are heavily loaded with natural oils, as contrasted to the starches of corn. Figure 3 shows a dissipation factor curve of

sunflower, as a function of frequency. At higher temperatures the dissipation factor rises just as in corn, however the magnitude of this change is considerably larger. We have not yet tested the sunflower seeds at low temperatures to compare with the corn values.

The original assumption, that perhaps increased thermal energy might be freeing molecular dipoles for easy reorientation, appeared less likely due to the lack of any specific frequency band. And, or course, at low frequency range where the dissipation factor increases markedly, it seemed quite unlikely that this was a molecular effect. During a search for a suitable explanation, a paper by J. Ross MacDonald[1] appeared which offered some interesting possibilities. This paper develops a theory of behavior for AC characteristics of either solids of liquids which contain charge carriers but have blocking electrodes. A general solution is given for the admittance of such materials, and useful comparisons are made with other similar theories. The quantities used in the calculations are in most cases available from our current data with the simple exception that we have been using equivalent resistance where MacDonald uses equivalent conductance. A somewhat more important difficulty was discovered in finding the limiting high frequency value of conductance, since as previously mentioned, our high frequency measurements are not good. There was also a minor problem in measurement of DC capacitance of the dielectric cell and seeds, but this has been satisfactorily approached by extending bridge measurements to 30 cps and then extrapolating. Thus we have made a preliminary graph of parallel capacitance/DC capacitance, but have so far been unable to do this for the conductance ratios.

The importance of being able to construct graphs of this type lies in the fact that MacDonald has given parameters which control the shape of the curves, and these parameters directly relate to the ionic conditions within the seeds. Satisfactory completion of these measurements would give us charge, sign, mobility, diffusion constants and perhaps valences of the mobile ions within the cells of the seeds.

It was at first thought that certain rational assumptions might be made concerning some of these values and curves calculated to match the experimentally derived curve of capacitance ratio mentioned above. However, this involves some formidable computation and personal communication with MacDonald reveals that this type of work is best done on computing machines, such as the IBM card programmed calculator used for his work. During this period it was also found that a plot of equivalent parallel resistance against frequency on logarithmic coordinate paper gave a rather sensitive method of detecting deviations at any frequency. Figure 4 shows this type of graph and illustrates that a straight line relationship is shown above a certain frequency for the experimental cases. It is also to be expected that R_p against frequency on log paper will give a straight line, provided that the dissipation factor remains constant. Thus we may easily see any changes in dissipation factor.

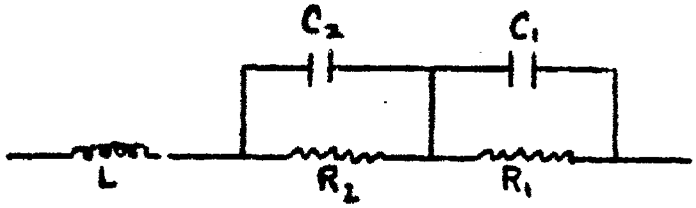
A paper by Kallman, Kramer, and Perlmutter[2] has offered some further possibilities for explanation of the low frequency results. Their paper on AC impedance measurements in luminescent powders describes changes similar to those observed by us as a function of temperature. They ascribe their observed results to the fact that certain portions

of the powder remain relatively nonconducting (mainly the surfaces) while the inner parts may become conducting under the influence of exciting radiation. In the case of the seeds, of course, it is assumed that charge carriers are increased in mobility by increasing the temperature, or that the total number of carriers has increased. The analogy is reasonably good, since the seed has a practically non-conducting surface with a feebly conducting interior.

Kallman et al. furnish curves of the variation of Q with exciting radiation, which show a pronounced minimum. Our curves when translated into this form show a continuous increase but no maximum at the temperatures so far attained. (The curves are inverted due to the use of equivalent parallel resistance instead of series resistance). Their explanation of this is that Q would be high for low conductivity, decreasing when conductivity begins to increase and rising again when the material becomes strongly conductive.

In order to obtain further information, a series of experimental points were taken for Ear-bred seeds at room temperature, at -14°C, and after dehydration in a vacuum of 10^{-4}mm. for 2 weeks. The results of this are shown in Figure 2, where it may be seen that the frequency characteristic of dissipation factor at freezing temperatures is almost identical with that taken after dehydration. There is still a trace of low frequency rise but far less than that observed in the normal seeds. When these values are translated to parallel resistance they appear as shown on Figure 4. Here it may be seen that the dehydrated corn follows nearly a straight line at all frequencies, indicating little change in the internal conductance.

The shape of the equivalent parallel resistance curves vs frequency suggested that an attempt be made to form an electrical model which would perhpas explain some of the observations. The simplest procedure is to consider two seeds in contact. This gives us a contact resistance R_1 and a capacitance between the two of C_1. The internal resistance of one seed is R_2 and its self capacitance is C_2. For generality, a provision should be made for an inductive term, L. This type of circuit is shown here:



The complete expression for R_p when all terms are included is a bit too unwieldly to include here, but certain reasonable simplifications may be made, depending on the interpretation of the model. If we select R_1, R_2 and C_1 only, the expression becomes:

$$R_p = \frac{\omega^2 R_1 R_2^2 C_1^2 + (R_1 + R_2)^2}{\omega^2\, {}_2R_1^2 C_1^2 + (R_1 + R_2)}$$

When we include the above terms and add C_2, we find that:

$$R_p = \frac{\omega^2 R_1^2 R_2^2 (C_1 + C_2)^2 + (R_1 + R_2)^2}{\omega^2 (R_1 R_2^2 C_2^2) + \omega^2 (R_2 R_1^2 C_1^2) + (R_1 + R_2)}$$

The final possibility for this situation is with only C_1, C_2, and R_2, which gives:

$$R_p = \frac{1}{\omega^2 C_1^2 R_2} + \frac{R_2 (C_2 + C)^2}{C_1^2}$$

In any case, these expressions may be used to give curves similar to those in Figure 4, when used with a judicious selection of constants. The major factor of importance for us is that when R_2 is decreased, we get curves which show a [illegible] R_p at low frequencies, which duplicates the experimentally observed situation when the seeds are heated or are in a non-dehydrated condition.

CONCLUSIONS OF CURRENT PERIOD:

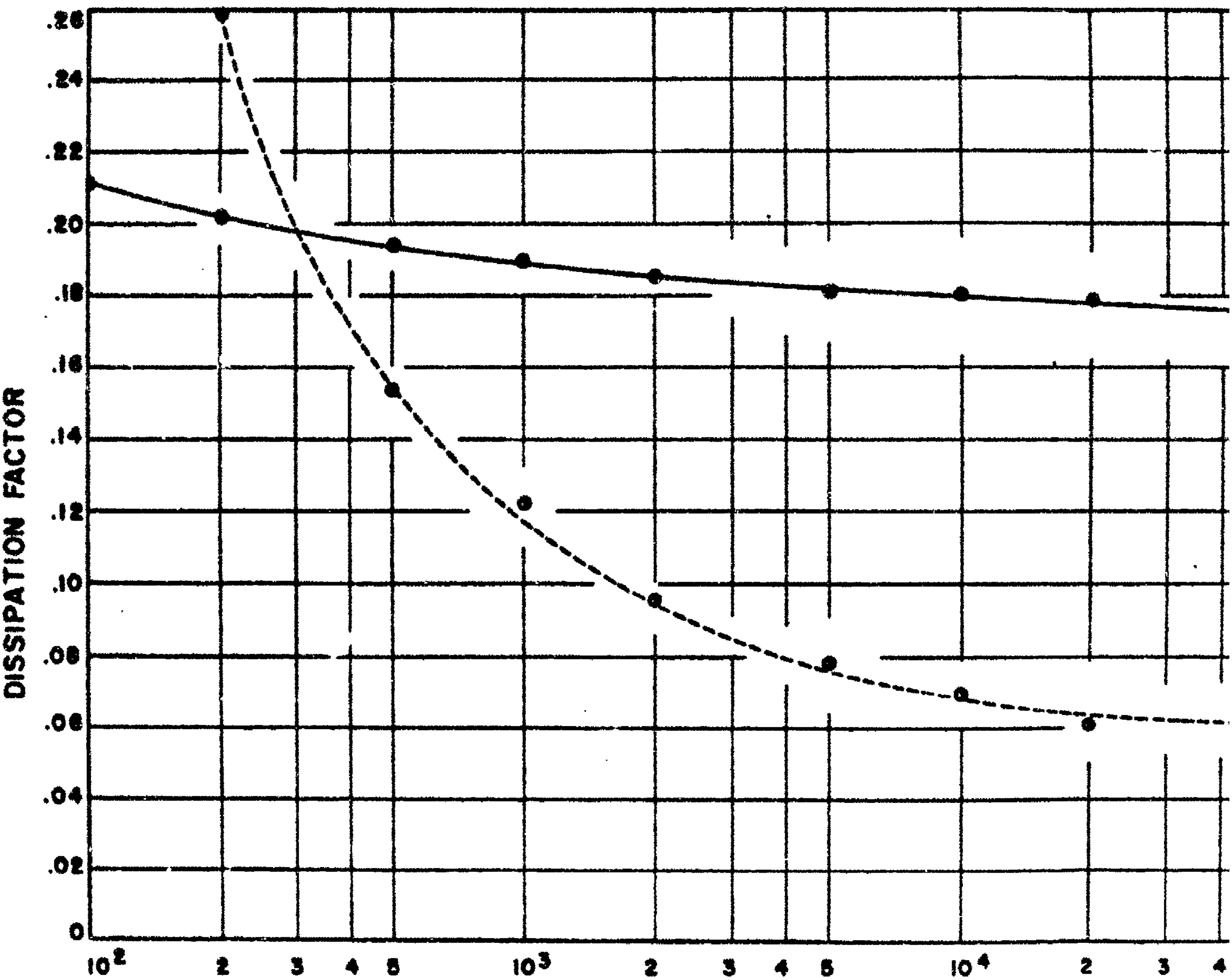
The lethal effects observed after 20 megacycle irradiation are most probably due only to heating. At the low frequency end of the measurements, the greatest probability is that the observed effects are nearly all due to ionic conduction within the seeds. It is assumed that the conduction mechanism is very sensitive to small amounts of water, as indicated by large changes in dissipation factor produced by freezing and nearly identical changes produced by dehydration. No definite statement may yet be made on the changes in conduction mechanism produced by heating.

The large increases in dissipation factor and the increase in dielectric constant at low frequency are thus due not to molecular reorientation but ionic polarization effects.

References:

1. J. Ross MacDonald, "Theory of AC Space-Charge Polarization Effects in Photoconductors, Semiconductors, and Electrolytes" Phys. Rev. 92, no. 1, pp. 4-17, Oct. 1953.

2. Hartmut Kallman, Bernard Kramer, and Arnold Perlmutter, "Induced Conductivity in Luminescent Powders. II. AC Impedance Measurements" Phys. Rev. 89, no. 4, pp. 700-707, Feb. 1953.



DISSIPATION FACTOR
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
10^2
2
3
4
5
10^3
2
3
4
5
10^4
2
3
4

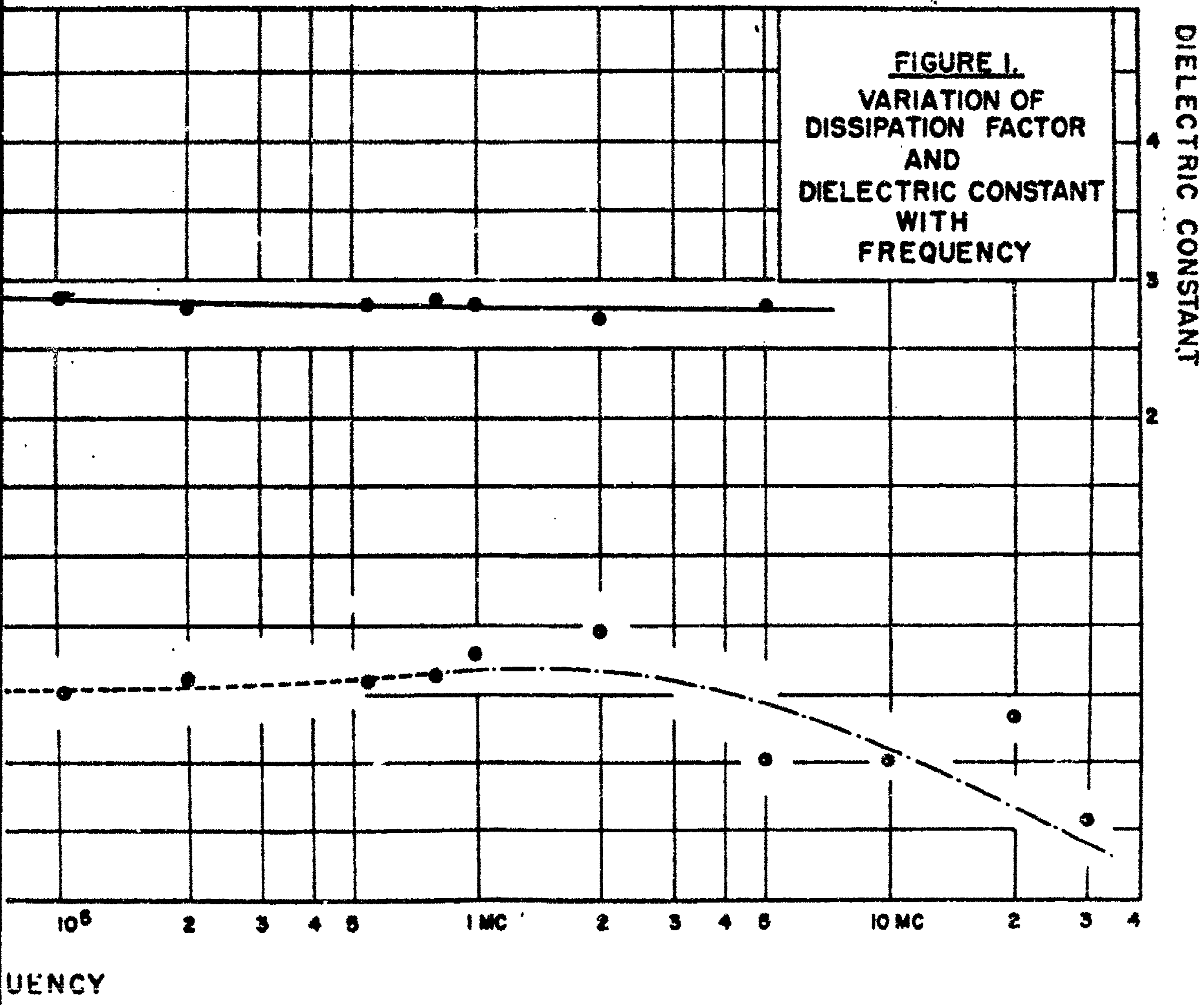


FIGURE I.
VARIATION OF
DISSIPATION FACTOR
AND
DIELECTRIC CONSTANT
WITH
FREQUENCY
DIELECTRIC CONSTANT
4
3
2
10^6
2
3
4
5
1 MC
2
3
4
5
10 MC
2
3
4
UENCY

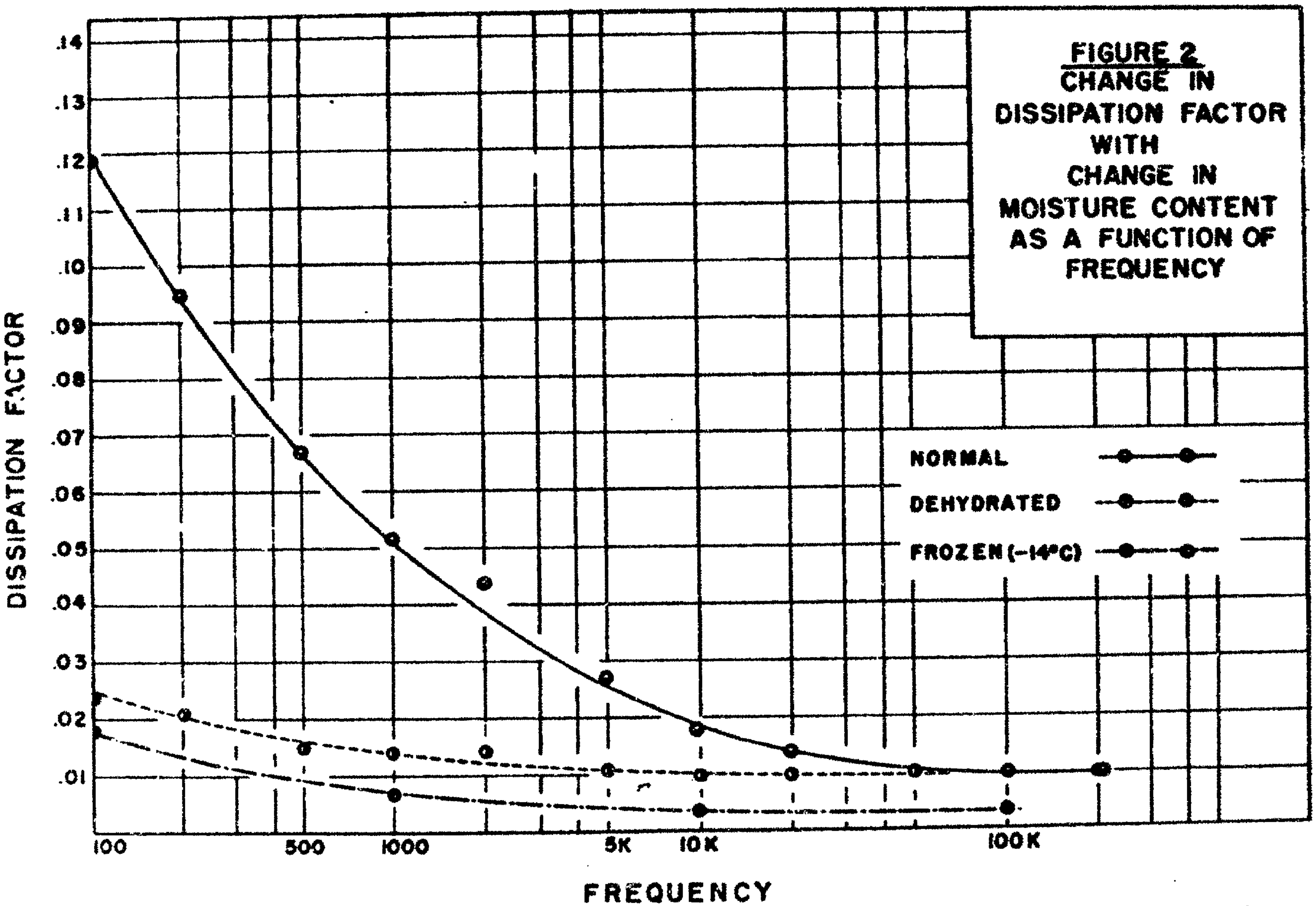


FIGURE 2
CHANGE IN
DISSIPATION FACTOR
WITH
CHANGE IN
MOISTURE CONTENT
AS A FUNCTION OF
FREQUENCY
NORMAL
DEHYDRATED
FROZEN (-14°C)
DISSIPATION FACTOR
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
100
500
1000
5K
10K
100K
FREQUENCY

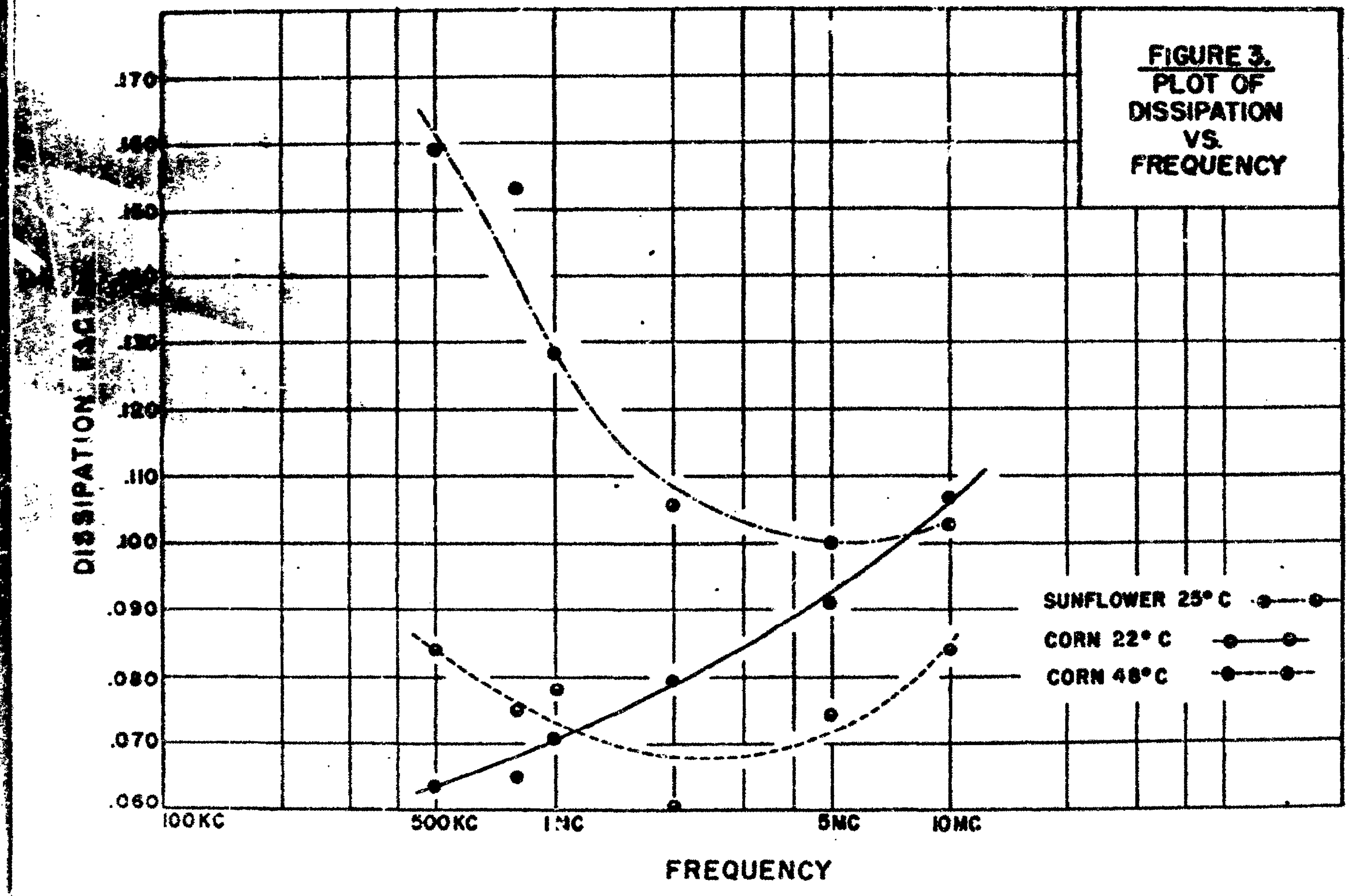


FIGURE 3.
PLOT OF
DISSIPATION
VS.
FREQUENCY
SUNFLOWER 25° C
CORN 22° C
CORN 48° C
.170
.110
.100
.090
.080
.070
.060
100KC
500KC
5MC
10MC
FREQUENCY
DISSIPATION

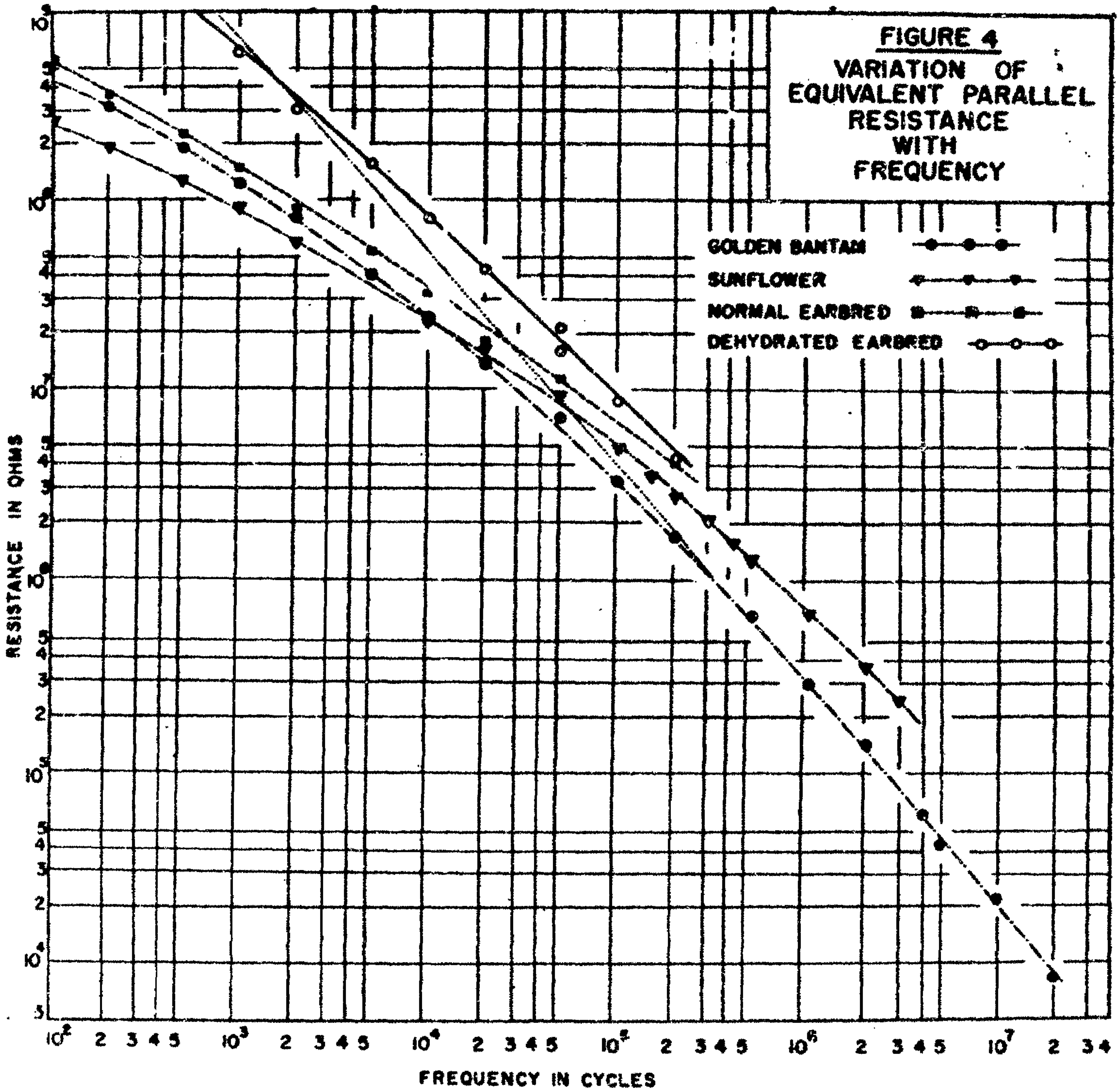


FIGURE 4
VARIATION OF EQUIVALENT PARALLEL RESISTANCE WITH FREQUENCY
GOLDEN BANTAM
SUNFLOWER
NORMAL EARBRED
DEHYDRATED EARBRED
RESISTANCE IN OHMS
FREQUENCY IN CYCLES